Tomographic & Geophysical Inversions from Opportunistic Sound Sources Aaron Thode

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LONG-TERM GOALS

The fundamental goal is to develop an advanced passive acoustic monitoring system that can be used to characterize ocean acoustic phenomena in ocean regions that are currently too isolated or remote to justify expensive exploratory research, and to provide cost-effective means to conduct field research into advanced coherent beamforming and geoacoustic inversion,methods The work also seeks to stimulate the further development of low-cost, low-power, autonomous acoustic recorders, by demonstrating how passive acoustic time-synchronization techniques can effectively convert a set of these recorders into a coherent beamforming array.

OBJECTIVES

To develop and demonstrate modular passive acoustic systems for studies in three-dimensional acoustic tracking and geoacoustic inversion, by exploiting advances in low-power recording technology, and by using knowledge of ambient noise spatial structure to time-align independent recorder records without the need for active timing sources. Connecting single-channel recorders with rope and/or fishing gear can create a modular "instarray" that can be arranged with variable aperture, hydrophone spacing, and orientation. This array system is easy to transport and deploy in less-than-ideal circumstances. These systems can be used to perform acoustic inversion and tracking studies using opportunistic sounds such as marine mammal vocalizations.

APPROACH

Marine mammal acoustic tag technology developed by Bill Burgess of Greeneridge Sciences Inc. has been modified to produce autonomous acoustic array "elements," which then can be arranged in a variety of configurations (Figure 1). The fundamental technical challenge for this effort is developing techniques for correcting relative clock offset and drift to the precision required for phase-coherent tracking (e.g., beamforming and matched-field processing). Three strategies for time-aligning autonomous recorder clocks have been examined:

(1) exploiting the ambient noise spatial coherence,

(2) exploiting multipath or "virtual hydrophones," and

(3) using discrete opportunistic acoustic sources to simultaneously localize and time-align hydrophones.

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14. ABSTRACT
The fundamental goal is to develop an advanced passive acoustic monitoring system that can be used to characterize ocean acoustic phenomena in ocean regions that are currently too isolated or remote to justify expensive exploratory research, and to provide cost-effective means to conduct field research into advanced coherent beamforming and geoacoustic inversion,methods The work also seeks to stimulate the further development of low-cost, low-power, autonomous acoustic recorders, by demonstrating how passive acoustic time-synchronization techniques can effectively convert a set of these recorders into a coherent beamforming array.

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WORK COMPLETED

- Halfway-point in program (a one-year no-cost extension has been requested).
- Data collected and analyzed:
    - Matched-field processing (MFP) of humpback whales in Australia, 2003, participation courtesy of Humpback Acoustic Research Collaboration (HARC). The ability has been demonstrated to simultaneously invert for source range and depth, ocean bottom interface speed, and recorder timing offsets and drifts.
    - Range-depth tracking of sperm whales in Alaska using large-aperture vertical arrays.
    - Gray whale data recorded in San Ignacio Lagoon, Baja Mexico Sur to demonstrate the use of ambient noise to determine element separation and time-syncrhonization, converting two bottom-mounted recorders into a short-aperture horizontal array.

RESULTS

Time-synchronization of autonomous recorders to sub-millisecond resolution has been achieved in both vertical and horizontal configurations, and geoacoustic inversion from an opportunistic marine mammal call has been demonstrated.

Vertical Array: A modular vertical array has been assembled, by attaching a set of autonomous recorders to a rope (Figure 1). The elimination of inter-connecting wires resulted in a lightweight, robust system that can be deployed in multiple configurations from very small vessels while consuming little power. The system tradeoff is that the data cannot be monitored in real time, and that more computational effort must be expended to synchronize the recorded acoustic data.

Work off Australia as part of the HARC programin 2003 and 2004 demonstrated that for the particular geometry of a vertical array in a shallow ocean waveguide, sufficient information exists in both a marine mammal acoustic signal and the ambient noise background to synchronize the data across the recorders, locate the source in range and depth, and invert for simple bottom parameters (Figures 2-4).

The relatively high clock drifts between the autonomous recorders can be determined by correlating the diffuse ambient noise background (Figure 5). The technique is described further in the publication listed under "Publications".

The time-aligned data can then be applied to a conventional MFP tracking algorithm (Figure 6). This result is only the second peer-reviewed result of applying coherent MFP methods to a marine mammal, and would not have been logistically possible without using this "insta-array" system.

Horizontal Array: In Feb. 2005 four sets of two-element horizontal arrays were deployed on the ocean floor in San Ignacio lagoon. By cross-correlating the ambient noise between the hydrophones, it was shown that the element separations, clock offsets, and relative clock drifts between the two sensors could be derived, replicating earlier results at the Marine Physical Laboratory, (K. G. Sabra, P. Roux, A. M. Thode, G. L. D'Spain, W. S. Hodgkiss, and W.A.Kuperman, "Using ocean ambient noise for

array self-localization and self-synchronization," accepted by IEEE Ocean Eng.). Figure 7 shows an illustration using data from the lagoon.

IMPACT/APPLICATIONS

The acoustic system developed under this proposal has been useful as a rapid prototyping system that has led to more dedicated hardware and launched other programs effort. Examples include a dedicated large-aperture towed array system funded by the Minerals Management Service (MMS) and the seismic exploration industry, funds from the North Pacific Research Board (NRPB) to study sperm whale behavior off Alaska, and the rapid performance characterization (in 2004) of a glider prototype based at MPL, which has helped support a large-scale development effort for the PLUS program under Gerald D'Spain.

TRANSITIONS

As mentioned, concepts demonstrated by this array have led to applications funded by the Minerals Management Service and the North Pacific Research Board (NPRB. The glider prototype instrumented by these autonomous recorders is being developed into a fully operational system, funded by ONR Code 321(OE) under Tom Swean.

RELATED PROJECTS

Three-dimensional tracking of sperm whales using passive acoustic monitoring: a project funded by MMS and the oil and gas seismic exploration industry, under the Sperm Whale Seismic Study(SWSS). The modular array system was used to demonstrate proof-of-concept of large-aperture towed array for tracking sperm whales, which lead to a dedicated hardware and software system. The software is scheduled to be implemented into a standard acoustic software monitoring package to be used by the industry.

Acoustic analysis of sperm whale long-line depredation in Alaska: funded by NPRB to understand how sperm whales are taking fish from commercial longliners, with the goal of suggesting means of reducing depredation. The modular array system is being used to convert longline deployments into large-aperture vertical arrays to track the motion of sperm whales around the gear. Simultaneous deployments at multiple locations have been achieved in 2005, and in collaboration with Chris Tiemann at APL-UT individual sperm whales have been tracked when fishing vessels are present and absent.

PUBLICATIONS

"A portable matched-field processing system using passive acoustic time synchronization," A.M. Thode, P. Gerstoft, W.C. Burgess, K. Sabra, M. Guerra, M.D. Stokes, M. Noad, and D.C. Cato, IEEE J. Ocean. Eng (accepted, in press).

HONORS/AWARDS/PRIZES

Internal SIO promotion: In Jan 2005 internal committee voted 17-0-1 to promote Thode to Associate Researcher rank. Development of modular array system was specifically cited as one reason for the promotion. Promotion approved by SIO office and new position began July 2005.

2005 AB Wood medal, UK Institute of Acoustics/Acoustical Society America: "for meritorious research in ocean acoustics and marine mammal acoustics".

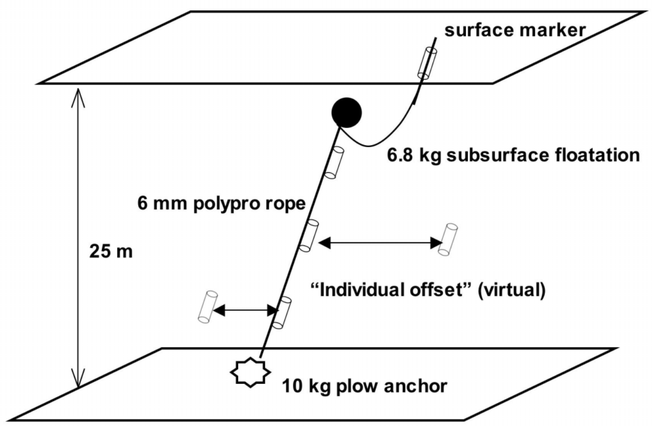

Figure 1a: Schematic of deployment geometry of modular autonomous vertical array, or "instarray," off Australia, in 2003 and 2004.

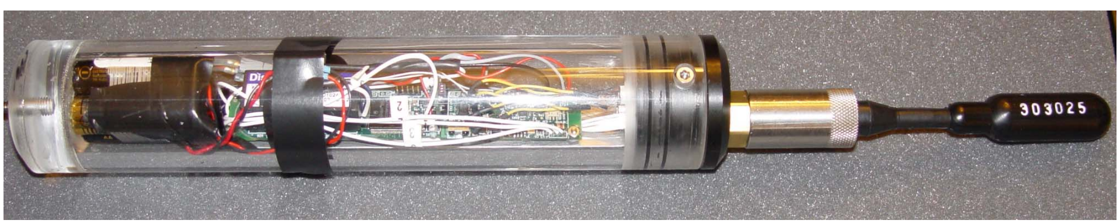

Figure 1b: Photograph of an autonomous element. Pressure case is 9 inches long.

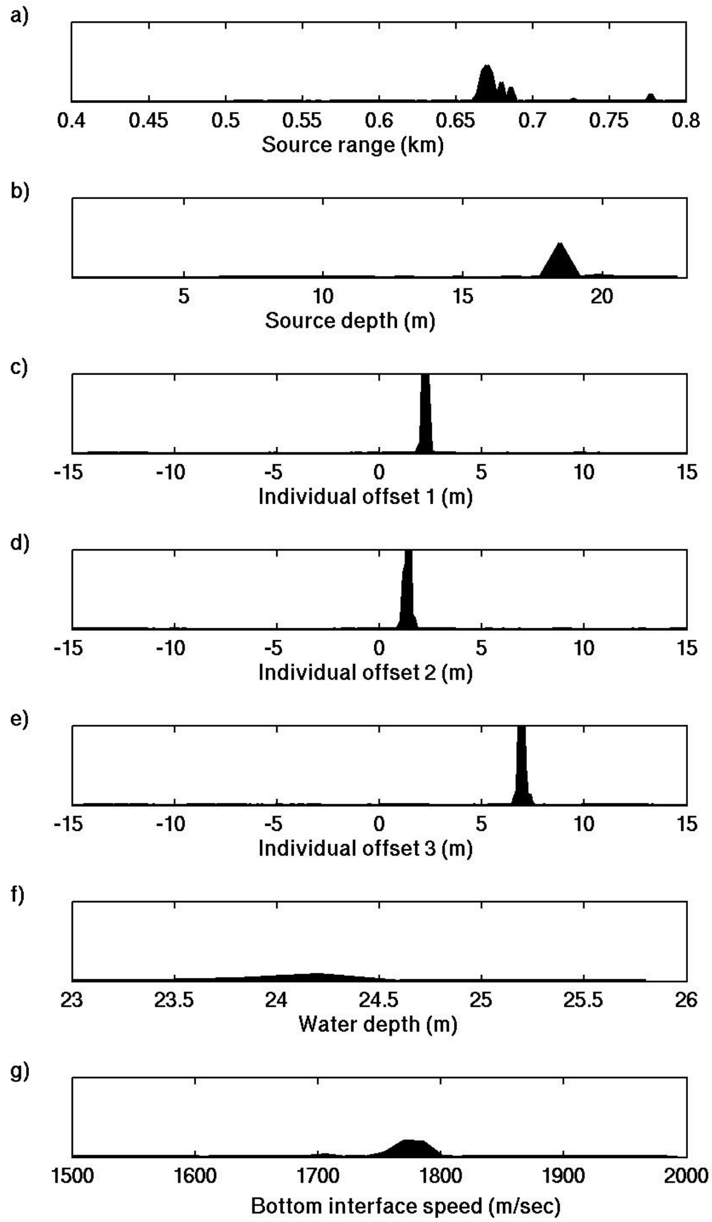

Figure 2: Histogram of inversion results of 20 SAGA runs for humpback song unit recorded at 11:52:51, Oct. 23. Key inversion parameters are inverted whale range (a), depth (b), relative virtual range offset of the three bottom hydrophones with respect to the shallowest hydrophone (c-e), ocean depth (f), and bottom interface sound speed (g). The figure illustrates how all of these parameters can be consistently inverted.

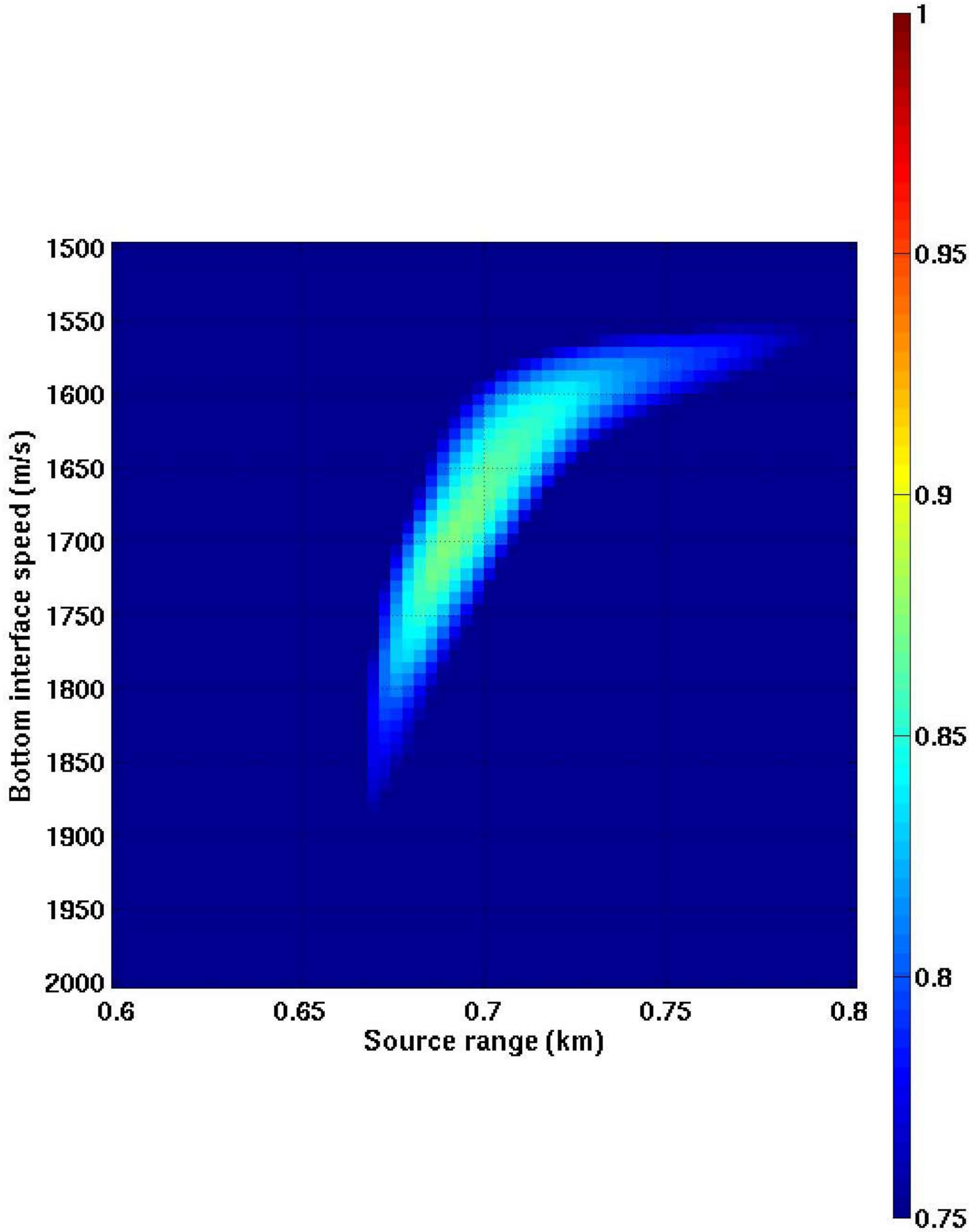

Figure 3: Ambiguity plot of source range vs. bottom speed derived from 10 frequency components (between 50 and 1000 Hz) of humpback whale song on 11:52:51, Oct. 23. Note the coupling between the parameters. Nevertheless a bottom sound speed between 1650 and 1700 m/s can be inferred. This information may be useful in modeling future playback experiments to marine mammals in the area.

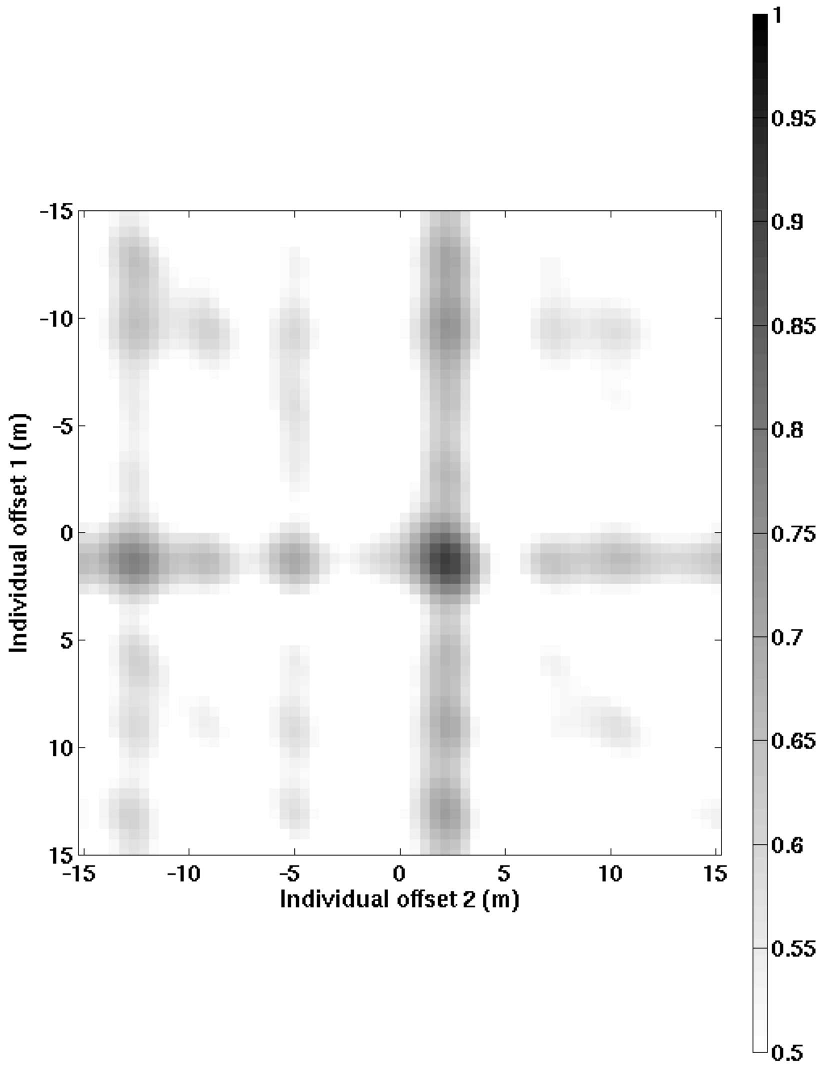

Figure 4: Bartlett ambiguity surface of 11:52:51 whale call computed along different clock offsets for hydrophones 1 and 2 (labeled here as "individual offsets"), with all other optimized parameters held fixed. The horizontal separation between the mainlobe and the horizontal sidelobe corresponds to the wavelength of the lowest frequency component in the ambiguity surface. The figure shows that there is no ambiguity about what the inverted clock offsets should be.

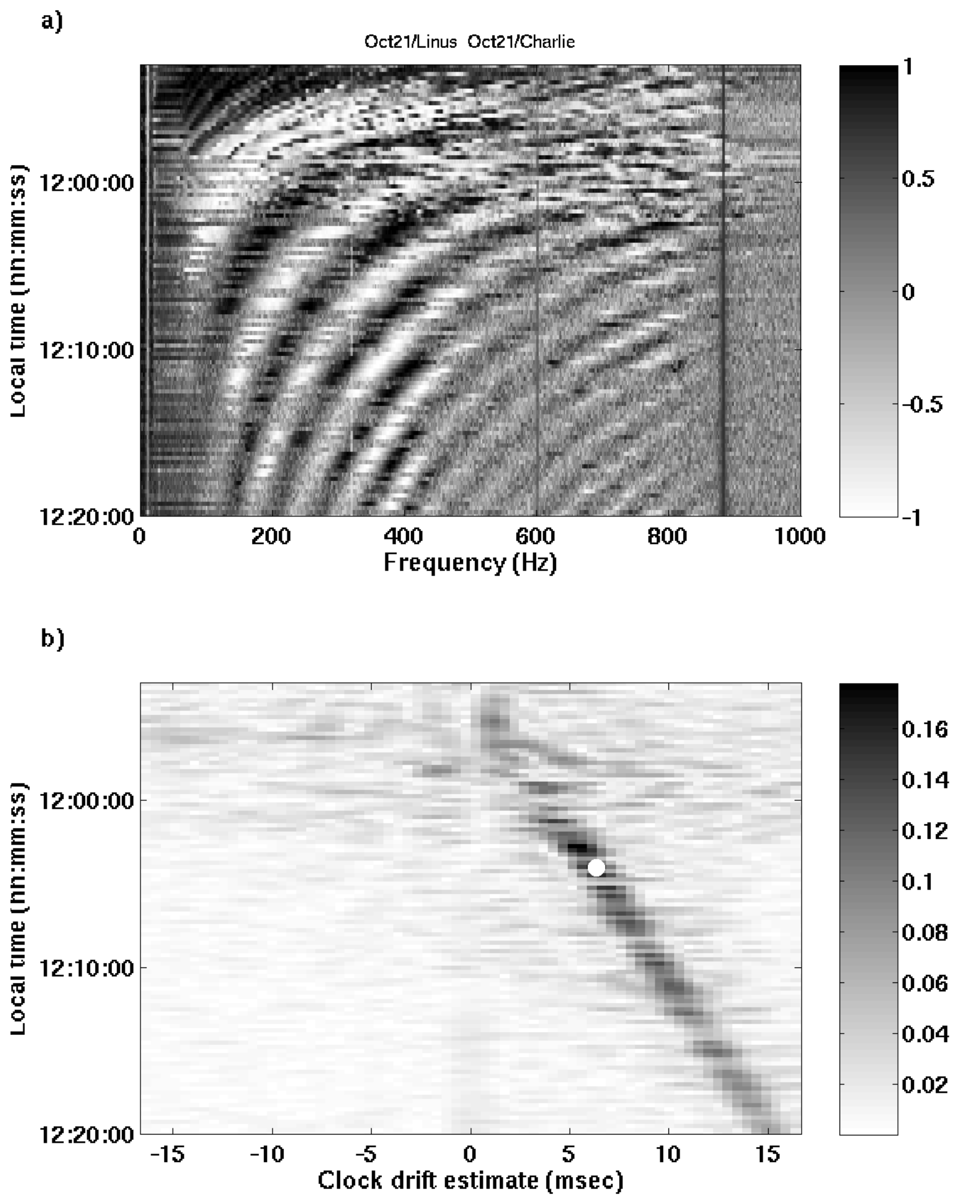

Figure 5: (a) Normalized spatial coherence as a function of frequency and local time; (b) Inverse Fourier transform of a) along horizontal axis. The horizontal axis is in units of milliseconds of drift. Plots were generated by averaging 10 s worth of data every 15 s over a 50 min time interval. An FFT size of 1024 pt with 75% overlap was used. The shift of the prominent streak in (b) provides a measurement of the relative clock drift for this hydrophone pair. The white circle shows the range offset derived from a second geoacoustic inversion at 12:04.

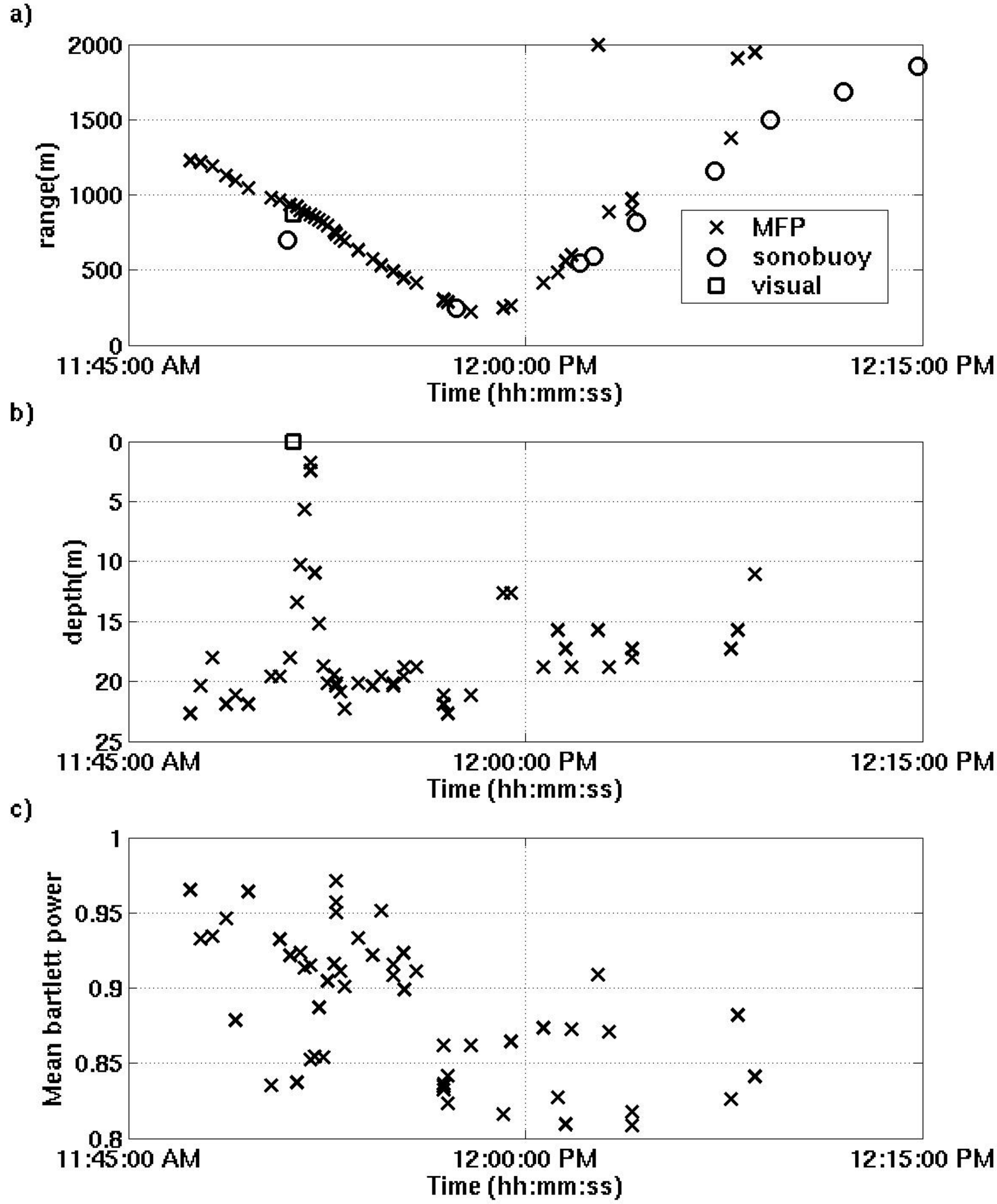

Figure 6: MFP track of humpback whale using best-fit propagation environment derived using data at 11:52:51, and using clock-drift measurements from ambient noise to re-synchronize data. (a) range of whale in meters from array site. 'x' represents an MFP location, 'o' is an independent hyperbolic fix using the moored hydrophone array, and the square represents a visual sighting of a surfacing animal. (b) whale depth vs. time. A surfacing of the animal at roughly 11:52 is visible, associated with a visual sighting. (c) mean Bartlett power averaged over frequency. Note the drop in correlation after the animal swims by the array.

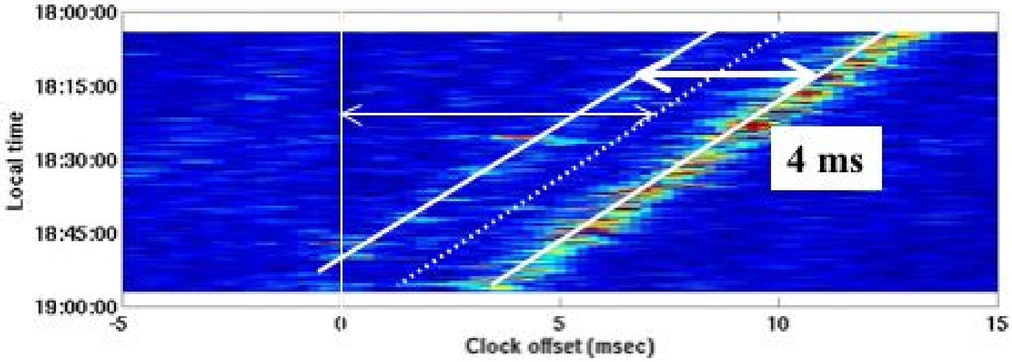

Figure 7: Illustration of how element separation, clock offset, and relative clock drift between two bottom-mounted recorders can be inferred from cross-correlating ambient ocean noise in San Ignacio Lagoon, Baja Mexico. The thick white arrow between the two peaks in the function yield element separation (4 ms ÷ 2 x 1.5 m/ms= 3 m separation), the thin white arrow shows a clock offset of 6 ms at 18:20 local time, and the slope of the white lines tracing the time evolution of the peaks yields clock drift.